Bits, Bangs or Bucks? The Coming Information Crisis–Part II

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Editor's note: This is the conclusion of an article on rising challenges in information modeling. The author previously argued that currently available analytical techniques lead to normative models that are at best caricatures of real situations (September 2001 PHALANX). In this conclusion, he extends his remarks to include evaluative models.

The role of information on the battlefield is fomenting a crisis in military operations research. It is clear to military professionals that information is becoming increasingly important, but the OR profession's ability to measure the contribution of information is still primitive. This article highlights the approaching crisis by surveying techniques currently available for measuring information. We are not even sure how information should be measured — is it measured in bits, bangs, bucks, or what?

Evaluative Models

Model types described earlier (decision theory, optimization, probabilistic dynamic programming, heuristic and game theory) are *normative*. Perhaps information would be easier to represent accurately if our analytical goals were less grand. The *evaluative* models considered here do not attempt to automatically manipulate a decision, nor do they even necessarily have a formal idea of what a decision is, so they are spared many of the constraints and artificialities that normative models require.

Mathematical Models

The title of this subsection is meant to restrict interest to evaluative models that include neither random number generators (Monte Carlo models are the subject of the next subsection) nor human subjects, but it is not meant to imply determinism.

The classic example of an evaluative mathematical model is a system of Ordinary Differential Equations (ODEs), especially Lanchester systems where the state variables represent surviving numbers of combatants. ODE systems are appealing because systems with thousands of equations can be easily solved as a function of time, and time sensitivity is particularly important in modeling information. **Cebrowski** states that "The principal utility of information superiority is time — the immense advantage of being able to develop very high rates of change." [1]

ODE systems are also appealing because they allow a graphical description, at least for a small number of state variables. Figure 1 is an example with six state variables, each named inside a circle with the initial value shown in the lower half. The arrows are labeled by formulas that show the *rate* at which one kind of thing is converted to another. For example the rate at which *BL* ("Blue Live") units are converted to *BD* ("Blue Dead") units is $b(LU+LI)$, with $LU+LI$ being the number of red Live Unidentified units plus the number of red Live Identified units (red names omit the initial *R* to limit the length of variable names). In other words, all live red units fire at blue in the classic Lanchester aimed-fire manner, with *b* being the number of blue casualties per red man-day.

The dynamics among the four red state variables is more complicated. *LU* units must be converted to *LI* units by an information system before they can be killed, and *LI* units may again become *LU* units if they are not killed quickly enough. *LI* units may also become either *DL* (Dead looking Live) or *DD* (Dead looking Dead). Since blue is assumed unable to distinguish *LI* from *DL* targets, the appropriate fraction of blue's fire is devoted to *DL* targets. This reduces the rate at which *LI* units are killed, but has the side benefit of gradually converting *DL* to *DD*. This long description of Figure 1 is meant to make the point that considerable detail is possible even with only six state variables. It should be clear that considerably more complicated scenarios could be expressed graphically on a single page.

Once the six technological parameters (a, b, p, q, s, t) are specified by the analyst, the information in Figure 1 determines the course of the battle between red and blue. Furthermore, the six equations can be easily solved dynamically in a spreadsheet. For example, using a time step of 0.1 day, the number of blue survivors on day 4 if the parameters are (0.5, 0.2, 0.4, 0.4, 2.0, 0.5) is 61.63, or it is 50.51 if the parameters are (0.3, 0.2, 0.4, 0.4, 5.0, 0.5). The second case can be thought of as one where blue spends more on information systems (the surveillance parameter s is increased from 2 to 5) at the cost of spending less on firepower (the firepower parameter a is reduced from 0.5 to 0.3). By this measure spending more on information is a mistake. The reason is that s is so high even in the first case that all of the *LU* units are converted almost instantly to *LI* units. Blue's problem is one of firepower, rather than surveillance. The problem could be rigged, of course, to make the decision go the other way. The point is merely that such systems can be the basis for tradeoffs between bits and bangs.

A smaller ODE example in the same vein is **Schreiber**, who analyzes a Lanchester model where information partially permits the direction of fire away from enemy targets that have already been killed.[2]

Both of these examples might be said to include information as an enabler: one either has information about certain objects or not, and having information about them enables certain activities that would not otherwise be possible.

ODE systems are so easy to solve that the analyst's problem is more likely to be one of acquiring data than one of computation. There is no computational reason why models with thousands of state variables could not be solved. Expected-Value Analysis (EVA) will necessarily be rampant in these models, since the state variables usually represent quantities that ought to be integers. However, there is a remedy in that the rates of change can always be interpreted as the rates of a Non-Homogeneous Poisson Process (NHPP). An NHPP model requires exactly the same information as an ODE model, but interprets it probabilistically, so a Monte Carlo simulation of the corresponding NHPP could be used as a kind of verification test for an ODE system. The hope would be that the ODE quantities can be interpreted

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as approximate expected values of the corresponding NHPP random variables. The automatic availability of the NHPP counterpart is another argument for the use of this kind of model.

The assumption in Figure 1 is that Red targets are always in one of only four states. As long as this is true, it is easy to explore the effects of changes in the transition rates. Unfortunately, it is easy to imagine circumstances where the number of states would have to be much larger than four. If targets have to be located as well as identified, then location accuracy (a standard deviation, perhaps) ought to be a target property, and it ought to be updated when multiple sightings occur or (for moving targets) when time passes. This would be easy enough if targets were tracked individually, but an ODE system simply *counts* the number of targets in a category. One might subdivide the LI category according to location precision. How fine should this partition be, and what should be done about transitions *out* of all the resulting states, as well as *between* them? To continue this line of thought, what if the *identity* of targets is not necessarily clear when a detection is made? Shall we introduce states such as "targets that are mobile missile launchers with probability 0.72 and school buses with probability 0.28"? Surely not. Questions such as these expose ODE systems for what they are: aggregated, low resolution models that are useful for investigating quantity questions when information is so simple that decision rules are obvious, but which suffer from state space and policy explosion when more subtle questions are posed.

A completely different type of evaluative mathematical model is the Bayesian network or Bayesian belief net, essentially an influence diagram with no decision or value nodes. Once built, a Bayesian network permits the user to test the influence of information about one thing on the probability of another in a simple and effective manner. There is a lot of current interest in Bayesian networks, witness the wealth of commercial software available (http://www.cs.berkeley.edu/~murphyk/Bayes/bnsoft.html).

However, Bayesian network construction suffers from its own kind of information explosion in the form of potentially large tables of conditional probabilities. Meanwhile, non-Bayesian approaches to

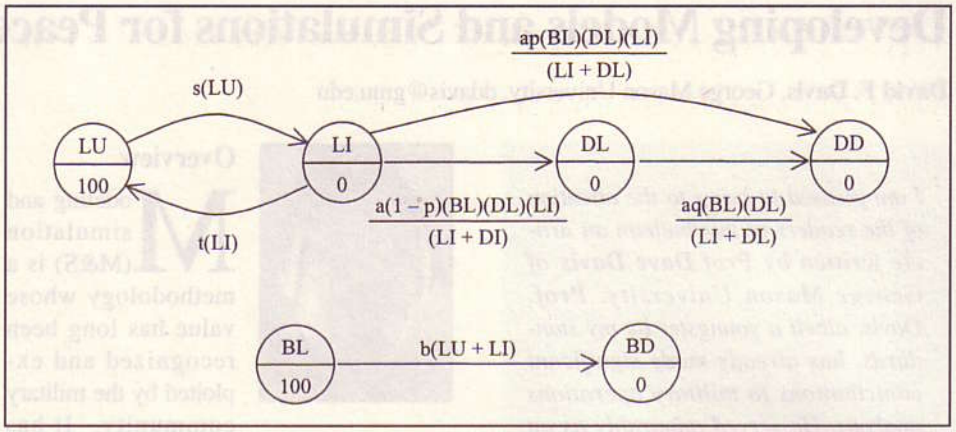

Figure 1. Information Warfare by Lanchester

uncertainty, such as influence nets that do not require these extensive tables, have their own perils.[3] In particular, it is all too easy to introduce quantities that are Interesting Rheostat Knobs (IRKs) in the sense that statements about them cannot be falsified. Once again, we analysts are confronted with a difficult choice about how to model information.

Monte Carlo Simulation

This modeling technique makes it possible to avoid EVA, since random variables can be sampled using a random number stream. Discrete random variables remain discrete, and the variability of combat results is evident because every replication is different. The computational cost is in the need for replication, since it is only by repetition that the distribution of results can be understood.

Monte Carlo is a very compelling paradigm. The variability of combat results is deliberately and scientifically included, and the avoidance of EVA permits a conceptual simplicity that is often impossible in mathematical models. It should therefore come as no surprise that many modern battle models are Monte Carlo simulations. This conceptual simplicity extends to modeling the effects of information, since it is possible and often useful to distinguish between truth and perception. The true and perceived versions of properties such as location, identity, and status can each be modeled explicitly.

The fusion of several sources of information is one area that illustrates the possibilities in a Monte Carlo model. Suppose we have a target moving in two dimensions, with information about its position being obtained occasionally from sensors. The fusion/extrapolation scheme might be simple dead reckoning from the latest sensor report, or it might be some more sophisticated scheme such as Kalman filtering. If a weapon is fired at the target, the effects of the weapon can depend on the fact that the true target location is known, at least to the analyst. A simulation would ordinarily take care to make sure that the true target location is not used in the aiming algorithm except through sensor reports, but the alternative of violating this principle for efficiency's sake is always available if needed. All of these possibilities are present in the Naval Simulation System, which offers several levels of fusion to the analyst.[4]

Monte Carlo simulations have similar advantages in many other aspects of warfare, including attrition, movement, and logistics. They capitalize effectively on regular improvements in computer technology, and deservedly hold the central place in warfare modeling. But even simulations are imperfect tools for demonstrating the value of information. Real military operations often hinge on good estimates of the situation. Many man-hours may be expended in estimating the one situation that actually unfolds, and even so the estimates are sometimes faulty. Partly because of the need for replication and partly because of the difficulty of capturing actual human decision making, this process must be heavily abstracted in a Monte Carlo simulation. The abstraction process is unlikely to capture optimal decision making, and therefore risks understating the effectiveness of information, especially if the information system is unfamiliar.

Consider Unmanned Aerial Vehicles

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(UAVs) used as reconnaissance platforms. One thing that distinguishes UAVs is that they are controllable in real time by humans on the ground that see whatever the UAV sees. This gives them an ability to investigate interesting observations, and through those investigations an ability to identify certain targets that would merely be detected by (say) a satellite. The usual sweep rate model will understate UAV effectiveness, but will still be tempting because UAV controllers are hard to simulate. The real military value of the information provided by UAV identifications may go unrecognized if such a model is used.

The ability to distinguish between truth and perception has been given as one of the advantages of simulation, but it turns out that truth is much easier to keep track of than perception. Consider the problem of fusing information about the locations of a collection of moving targets. A single-hypothesis correlator-tracker will typically think of the distribution of each target's two-dimensional location as a bivariate normal random variable. Bayes' theorem, on the other hand, will produce a multi-modal probability map when there are significant false alarm or false association rates.[5] There is a definite danger of losing the essence of the matter if the bivariate normal is employed to approximate the multi-modal distribution, and the loss is particularly to be regretted if the *point* of the simulation is to assess the value of information. The information analyst is confronted with an unwelcome choice between a simple model that is seriously wrong and a multi-modal model that, while it correctly represents the uncertainty of the decision maker, can easily slow down the simulation to the point of unusability. It is difficult to capture information fusion accurately and efficiently, especially under the constraint that the fusion algorithm must be fast enough to risk incorporating in a simulation.

It does not help that our subject is the value of *military* information. One lesson from game theory is that the enemy is motivated to behave in a confusing manner, so a tracker that might work well in tracking whales may not work so well in tracking submarines. Difficult decision making situations are the norm, rather than the exception, when there is a sentient enemy involved.

The value of information depends on how it is represented, processed and used. The classical decision theoretic representation, with its emphasis on Bayes Theorem, is logically impeccable but not computationally tenable within large-scale simulations of combat. We must face this fact, and we must also find representations that work.

The solution may lie in a distributed rather than centralized approach to decision making. Experiments involving goal-directed "agents" whose behavior is reasonable rather than optimal have revealed that surprisingly complex phenomena sometimes emerge even with very simple agents.[6,7] The Marine Corps' Project Albert, for example, uses agent-based modeling to construct models where non-linear, emergent behavior can be observed.[8] Perhaps a new paradigm is emerging where decision making is decentralized, and therefore simpler to model at each decentralized node.

Man-in-the-loop Simulations and Wargames

Humans are still very effective decision makers, especially in dynamic, competitive, foggy situations such as combat. It is tempting to give up on attempts at decision making in the abstract, and simply let humans make decisions on the basis of simulated information, especially since humans will have to make the decisions in actual combat anyway.

There is certainly a role for this approach, since the premises are good ones, but it is no panacea. There is a need for replication on account of the inherent variability in situations where information is important. Replication is always expensive when humans are involved, and there are special experimental difficulties when the participants are supposed to be uncertain but powerful decision makers. The participants should ideally be "naïve experts." They should be experts in the sense of knowing enough about the game to behave realistically, but they should be naïve in the sense that previous encounters with the game should not lead to anticipation of the random quantities that the simulated information system is supposed to be illuminating. It is not easy to obtain both of these properties in the same human. If the fog of war is taken from history or for other reasons difficult to sample, one might use different experts one time each to prevent anticipation. But all "experts" are not equally so, and there is consequently a danger of having the outcome be determined more by the expert than by the information system. One implication of these difficulties is that man-in-the-loop models are mainly useful for testing qualitative changes, rather than variations on a theme. They might be useful for finding out whether UAVs make a difference, but not for settling UAV design questions or measuring marginal changes.

When several humans with different goals are involved, a man-in-the-loop simulation becomes a wargame. Wargames and exercises involve some new issues in addition the to the statistical ones outlined above, but nothing changes the basic conclusion that models that rely on human decision makers are bound to entail statistical problems that limit their precision. As a result, they are best employed in comparing qualitatively different systems, rather than in investigating marginal tradeoffs.

Man-in-the-loop simulations, wargames and exercises have a strong role to play in *training*, and this role can only be enhanced by the virtual reality that is fast becoming possible with modern computers. But training must be distinguished from analysis, and we must be careful because the phrase "Modeling and Simulation" can mean highly different things in the two cases. Simulations that achieve realism by the incorporation of human decision makers are bound to be clumsy as *analytical* tools. They can still be valuable, but they cannot be central to our ability to evaluate information.

Summary

Our profession is poorly prepared to deal with the coming information crisis, especially for the kind of marginal questions that are involved in trading off information systems with firepower systems. We have all seen briefing charts where a lot of arrows point into a circle labeled "FUSION," and one arrow labeled "fused information" comes out. It is not that easy, and we would be wise to begin by admitting it.

Even so, the situation is not hopeless. While none of the techniques surveyed above are clearly indicated as the technique

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of choice, every one of them has been applied to problems involving information evaluation. With more effort put into sharpening and adapting our current tools, and perhaps inventing some new ones, we can possibly deal with the crisis. In the meantime, we should at least employ EVA, Time Reveals All (TRA) and IRKs more reluctantly, recognizing that they are particularly dangerous in models that claim to measure the value of information.

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OPERATIONS
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and installation management within an armistice environment, does this imply that the 34th and 20th Support Groups be divested of their base operation and installation management support responsibilities? Does this also suggest that separate, distinct support activities be created at Seoul and Taegu? There are other issues too numerous to mention in this essay. Suffice it to say, a trained Operations Research Systems Analyst (the author) is part of this study group. In addition to helping to solve the aforementioned questions, my responsibility is, also, to make sure that we (the Team) use analytical tools that are consistent with the study methodology to arrive at conclusions and recommendations that comply with the study's objectives. I also assume that these recommendations satisfy our decision criteria which include command and control considerations, cost effectiveness, and the ability of the newly established DBOS organization to respond to changes in the current operational environment. Eighth US Army isn't simply making a change for the sake of change. This forward deployed Command is using its highly professional Resource Management personnel – to include an erstwhile OR Analyst – to realize efficiencies. The prudent use and conservation of scarce public resources is the Resource Manager's most sacred obligation to the command, the Department, and the tax-payers.

Operations Research Systems Analysts have always managed and, in certain instances, maintained operational and performance databases. The wide application of local area networks throughout the services lends itself well to creating a centralized, command-unique Resource Management database to capture Program Objective Memoranda (POM), budget, execution, cost, installation status report, and manpower data. Select portions of the Training Resource Module (TRM) can also be imported into the command-unique database. Overseas commands can also capture host nation cost sharing contributions and local economic indicators – such as currency fluctuations which impact on foreign currency based budgets. Perhaps data concerning Joint and Combined resourcing could be captured. At any rate, this is yet another excellent area where ORSA can be used to analyze and interpret the data, graphically depict significant trends, prepare forecasts and make recommendations to Command decision makers. Fundamentally, the mission of ORSA professionals is to fully inform decision makers so they can make educated decisions. A command-unique Resource Management database is simply a tool that Operations Research Systems Analysts can use to keep decision makers informed of resource management concerns and issues.

Operations Research Systems Analysts will continue to perform the traditional roles of researching, developing, maintaining and applying models and simulations; managing databases, testing equipment and creating standard operational scenarios. However, more OR Analysts will be directly involved in conducting analysis to support the decision making processes at the headquarters and major command levels. The shrinking resources available to the departments will create a greater demand for this type of ORSA service. In these lean times, the military services should look toward the ORSA professionals on their staffs to analyze complex resource management problems and to arrive at conclusions and recommendations that help commanders, senior executives, and management make informed decisions about resourcing postures. ORSA is a viable skill that facilitates the integration of national command authority and Congressional resourcing actions to the services and, subsequently, to the major commands, subordinate commands, installations, and combat units. OR analysts could also use the data captured in command-unique Resource Management databases to point out significant trends, prepare forecasts, and make recommendations to decision makers about the command's resourcing posture to support armistice and wartime operations. LTG **Woodmansee** captured the essence of this paper when he said: "I want ORSA officers working for me because they are smart, not because they can crunch numbers." Why not let ORSA give you a helping hand in managing your resources?

Biography

John Di Genio, a trained ORSA, currently works as a Management Analyst with Eighth United States Army, the Assistant Chief of Staff, Resource Management, Manpower and Force Accounting Division. Previously, he worked as an Operations Research Systems Analyst at Headquarters, Combined Forces Command / United States Forces Korea, Assistant Chief of Staff, C/J1. Mr Di Genio has been awarded the distinction of being the Department of the Army Outstanding Resource Management Author in 2000. ✪